

## **SECTION 4. DISCUSSION**

### **THE EFFECT ON DRIVING PERFORMANCE OF TRAVELING UNDER AUTOMATED CONTROL**

The objectives of this experiment were: (1) to determine whether driving behavior would be affected by traveling for an extended period of time under automated control at a speed greater than the speed limit and with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead; (2) to determine the effect on the driver's post-AHS behavior of varying the distance between the driver's car and the vehicle immediately ahead while the driver was traveling in the automated lane; and (3) to determine the effect on the driver's post-AHS behavior of varying the method of transferring control from the AHS back to the driver as his/her vehicle left the automated lane.

Forty-eight drivers participated in this experiment. Thirty-six of these drivers were assigned to the experimental groups, while the remaining 12 were assigned to the control group. There was one experimental trial, lasting approximately 60 min, for each driver. In this trial, the drivers in the experimental group drove the simulator vehicle for the first 15 min of the trial. Then they traveled under automated control for at least 35 min, before controlling the vehicle again for the remaining 10 min of the trial. The drivers in the control group did not travel in the AHS; instead, they stayed in control of the simulator vehicle throughout the trial. Driving-performance data were collected for both groups during two time periods. For both groups of drivers, the early data-collection period, which lasted for 9.5 min, began at the start of the sixth minute of the trial and ended 14.5 min into the trial. For the drivers in the experimental group, the late data-collection period began as soon as control of the vehicle was transferred back to them by the AHS, and ended 9.0 min later. For drivers in the control group, the late data-collection period began at the start of the 52nd minute of the trial and finished at the end of the 60th minute. For analysis purposes, the late data-collection period was divided into nine 1-min segments so that it would be possible to determine the time course of any effects that travel in the AHS had on the driving-performance measures. The data obtained in these 1-min segments were compared with the driving-performance data obtained in the 9.5-min early data-collection period.

#### **Lane-Keeping Performance**

The first two driving-performance measures, steering instability and the number of steering oscillations, provided information about the driver's lane-keeping behavior. There was less steering

instability for drivers in both the control and experimental groups in the late data-collection period, specifically for the second through ninth minutes of data collection, than there was in the early data-collection period.

Since the reduction in steering instability was found both for drivers in the experimental group and for those in the control group, it is difficult to determine what exactly produced the effect. There could be a common cause: For example, as the trial progressed—whether the driver was in control of the vehicle or the vehicle was being controlled by the AHS—the driver would have become increasingly familiar with the feel of traveling in the simulator vehicle, and this increasing familiarity may have made the driver pay more attention to steering and have led to a reduction in steering instability. Alternatively, there may have been distinct and separate causes for the effect: For example, there may have been a reduction in steering instability for drivers in the experimental group during the late data-collection period because, after their vehicles had been controlled automatically and they had experienced travel in the simulator vehicle with relatively little steering instability, they may have attempted to reproduce this effect by steering as precisely as the AHS. On the other hand, the reduction in steering instability that occurred for the control-group drivers during the late data-collection period may have been the result of those drivers having repeated practice at steering in the earlier parts of the trial. At this point, without further experimentation, it is not possible to determine which of the various explanations is most likely to be correct.

The number of steering oscillations (i.e., the number of times the steering line of best fit was crossed per minute) was unaffected by the period in which the data were collected, the age of the driver, the intra-string gap, or the method of transferring control of the vehicle to the driver.

### **Speed Control**

The next four driving-performance measures all dealt with speed control. The first two variables, average velocity and velocity drift, are considered together. Traveling in the AHS had no effect on either average velocity or velocity drift; there were no statistically significant differences between the early and late data-collection periods for drivers in the control or experimental groups.

Statistically significant differences were found for the other two speed-control measures: average velocity instability and the average number of velocity fluctuations changed from the early to the late data-collection periods. Once again, however, the changes were found for drivers in both the control and experimental groups. The drivers' velocity instability decreased from the early

data-collection period to the first 1-min segment of the late data-collection period. It decreased again in the second 1-min segment, and then maintained this lower level throughout the remaining segments in the late data-collection period. There was an increase in the number of velocity fluctuations from the early data-collection period to the first two 1-min segments of the late data-collection period. There was a further increase in the third 1-min segment, after which this higher level was maintained throughout the remainder of the late data-collection period.

As the trial progressed, the drivers appeared to improve their speed control, reducing their velocity instability by making smaller, more frequent adjustments. However, as with the improvement in steering performance mentioned in the previous subsection, since the reduction in velocity instability and the related increase in velocity fluctuations were found both for drivers in the experimental group and for those in the control group, it is difficult to determine what exactly produced these improvements in speed control.

There could have been a common cause: For example, as a result of becoming more familiar with the feel of traveling in the simulator vehicle as the trial progressed, the drivers may have paid more attention to controlling the speed of the vehicle, as well as to steering it, in the late data-collection period. Or, there may have been separate causes of the improvements: For example, improvements may have occurred for drivers in the experimental group during the late data-collection period because, after their vehicles had been controlled automatically, they may have attempted to control the speed and steering of the vehicle as precisely as the AHS. On the other hand, improvements that occurred in the late data-collection period for drivers in the control group may have resulted from their repeated driving practice in the earlier parts of the trial. It might be expected that there would be greater improvements in driving performance for the drivers in the control group—who controlled the vehicle for a longer period of time—than there would be for the drivers in the experimental group—who were being driven by the AHS. There is some evidence to support this expectation: In seven of the nine 1-min segments in the late data-collection period, there was less velocity instability for the drivers in the control group, and in all nine 1-min segments, the average number of velocity fluctuations was greater for the drivers in the control group than for those in the experimental group. However, without more experimentation, this possibility cannot be explored further. [Note: The ANOVA's conducted on velocity instability and on velocity fluctuations (see tables 47 and 48 for the velocity instability ANOVA's and tables 49 and 50 for the velocity fluctuation ANOVA's) did not indicate that there were differences between the experimental groups and the controls. However, recall that the two-tailed sign test showed the statistically significant finding that in nine out of nine cases

the mean number of velocity fluctuations was greater for the control-group drivers than it was for the experimental-group drivers.]

### **Minimum Following Distance**

The minimum following distance was less in the late data-collection period compared with the early data-collection period, but there was no difference between the control and experimental groups. Thus, there was no obvious effect of automated travel on minimum following distance.

### **Time in the Center and Right Lanes**

The drivers in the experimental group spent significantly more time in the center lane (and correspondingly less in the right lane) in the early data-collection period than they did in the late data-collection period. They spent 82 percent of the time in the center lane in the early data-collection period and 65 percent there in the late data-collection period. In contrast, the drivers in the control group were in the center lane for 41 percent of the time in the early period, reducing this time only to 40 percent in the late period.

It is probable that the drivers in the experimental groups spent a large percentage of time in the center lane in the early data-collection period because they were aware that they would be instructed to move to the center lane in order to engage the automated system, and they were anticipating this event. Then, they spent less time in the center lane in the late data-collection period because, after traveling under automated control and being deposited in the center lane by the AHS, they moved to the right lane in order to take an exit ramp at the end of their journey.

The reason that the experimental group spent more time in the center lane in the late period than the drivers in the control group, even though they may have been anticipating leaving the expressway, was that they were deposited in the center lane by the AHS.

### **Lane Changes and Incursions**

Traveling under automated control for an extended period of time appears to have had no effect on either the number of lane changes or the size of the gaps accepted by drivers in the experimental groups. Similarly, driving in the simulator for an extended period of time appears to have had no effect on either the number of lane changes or the size of the gaps accepted by drivers in the control group.

However, there was a suggestion that traveling under automated control for an extended period of time may have resulted in some drivers attempting to change lanes into smaller gaps than those into which they attempted to change lanes before traveling under automated control. The smallest of the incursion gaps observed for the drivers who traveled under automated control for an extended period of time appears to have been shorter than the incursion gaps of the drivers in the control group. In the late data-collection period, there were 10 incursion gaps shorter than 40 m (131 ft) for drivers who traveled under automated control, while there were only 2 incursion gaps that were this short for these drivers in the early period. In comparison, for drivers in the control group there was one incursion gap that was shorter than 40 m (131 ft) in each of the data-collection periods.

### **Intra-String Gap and Method of Transferring Control**

The variations in intra-string gap and in the method of transferring control of the vehicle to the driver had no effect on subsequent driving performance. However, there were some responses to the questionnaire that related to the intra-string gap and the method of transferring control. With regard to the intra-string gap, when asked “When your car was under automatic control, how did you feel about the separation distance between you and the car ahead?” drivers responded that they would prefer longer gaps than those they experienced.

As to the method of transferring control, when asked how they felt about the way in which control of the vehicle was given back to them, drivers who were given control of both steering and speed simultaneously gave a significantly stronger positive response than drivers who first got control of the speed, and then subsequently got control of the steering.

## **OTHER EFFECTS**

### **Age of the Driver**

The age of the driver affected two performance measures: the average velocity and the percentage of time spent in the center lane. First, the younger drivers drove significantly faster than the older drivers; the average velocities, over both data-collection periods, were 87.5 km/h (54.3 mi/h) for the younger drivers and 84.2 km/h (52.4 mi/h) for the older drivers. It is to be noted that there is likely no practical significance to this difference. Second, the younger drivers spent more time in the center lane than did older drivers; the percentages were 70 percent and 59 percent, respectively.

## **Minimum Following Distance**

The minimum following distances obtained in this experiment were similar to values obtained by Ohta in a field experiment.<sup>(15)</sup> The 0.80-s average minimum following distance obtained in the current experiment after the drivers in experimental groups had traveled in the automated lane falls near the center of the 0.6 s to 1.1 s range that Ohta called the “critical range.” The average minimum following distances of just over 1.0 s that were obtained for drivers in the experimental group, before they traveled under automated control, and for drivers in the control group in both data-collection periods are close to the upper boundary of this critical range.

## **Lane Changes and Incursions**

The smallest gaps found for both accepted lane-change gaps and the rejected incursion gaps were very similar, between 40 m (131 ft) and 60 m (197 ft), suggesting that the minimum gap acceptable for a lane change is in this region. The drivers were driving at speeds close to the speed limit of 88.6 km/h (55 mi/h) in both the early and late data-collection periods. For a driver traveling at this speed, gaps of 40 m (131 ft) and 60 m (197 ft) are equivalent to gaps of 1.6 s to 2.4 s, respectively.

It should be noted that, although the minimum gaps when the drivers changed lanes and when they made incursions were similar in size, there was no correlation between the size of the gap a particular driver rejected when an incursion occurred and the gap that the same driver accepted when changing lanes.

## **IMPLICATIONS FOR THE AHS**

- (1) While it is not clear whether the experience of traveling under automated control produced the reductions in steering instability and velocity instability and the increased number of velocity fluctuations—all of which can be considered as improvements in driving performance—that were found for drivers in the experimental group in the late data-collection period (since similar improvements were found for the drivers in the control group), it is clear that the experience of traveling under automated control did not have an adverse affect on lane keeping and speed control.
- (2) Automated travel produced no obvious effect on minimum following distance.

- (3) The drivers in the experimental group spent more time in the center lane than drivers in the control group both before and after they traveled under automated control for an extended period of time.
- (4) The drivers who traveled under automated control expressed a preference for larger intra-string gaps than those that they experienced in this experiment.
- (5) The drivers in the experimental group who were given control of both steering and speed simultaneously gave a significantly stronger positive response when asked how they felt about the method of control transfer than the drivers who first got control of the speed and then subsequently got control of the steering.